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Estuary. A systems perspective

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Abstract

Estuaries are complex, dynamic ecosystems where freshwater meets saltwater, supporting diverse biological, physical, and chemical processes. Systems theory offers a holistic framework for understanding these environments by emphasizing interconnectedness, feedback loops, emergent properties, and hierarchical organization. This approach enables researchers and managers to identify root causes of ecological issues rather than addressing isolated symptoms. Emergy analysis, developed by Howard T. Odum (Odum 1983), provides a systems-based method to quantify all energy and material flows in solar emjoules, offering a unified metric for evaluating sustainability, ecosystem services, and human impacts. By applying systems principles, such as transformation of inputs, energy-material-information requirements, storage and structure, and feedback reinforcement, this study demonstrates how estuaries can be analysed and managed more effectively. Case studies from the Herring River Estuary (USA), mangrove restoration projects in Southeast Asia, and wetland conservation in the Liaohe Estuary (China) illustrate the practical value of systems thinking and emergy synthesis in guiding restoration and policy decisions. The article also reflects on broader implications, examining how systems thinking challenges capitalist reductionism and informs alternative economic models such as degrowth and circular economies. It highlights the importance of cultural re-engagement through literature and storytelling in fostering ecological awareness and collective action. Ultimately, integrating systems thinking into coastal management supports regenerative, equitable, and resilient strategies that align ecological health with social well-being. This work underscores the transformative potential of systems theory and emergy analysis in confronting global challenges such as climate change, biodiversity loss, and unsustainable development.

Key words: Biodiversity, Climate Change, Economy, Emergy, Sociology, Sustainability, System Theory, Thinking Systems

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Introduction

Estuaries are complex, dynamic ecosystems where freshwater meets saltwater, supporting rich biological, physical, and chemical processes. Traditional reductionist approaches often fail to capture the full complexity of these environments, leading to fragmented management strategies that address symptoms rather than root causes. This article applies a systems thinking framework to better understand and manage estuaries, emphasizing their interconnectedness, feedback mechanisms, and emergent properties.

Systems theory offers a holistic perspective that views estuaries not as isolated entities but as integrated components of larger ecological, economic, and social systems. By focusing on interactions and interdependencies, this approach enables researchers and managers to identify leverage points for sustainable interventions. A key method used in this analysis is emergy synthesis, a systems-based tool developed by Howard T. Odum that quantifies all energy and material flows in terms of solar energy equivalents. Emergy provides a unified metric for evaluating ecosystem services, human impacts, and sustainability trade-offs, particularly useful in estuarine contexts where natural and anthropogenic processes are deeply intertwined.

This article aims to demonstrate how integrating systems thinking and emergy analysis can lead to more effective, resilient, and equitable management of estuaries. It explores how systems principles, such as transformation of inputs, feedback loops, storage, and hierarchy, can inform decision-making and policy development. Additionally, it examines the role of systems thinking in addressing broader global challenges exacerbated by capitalist reductionism, such as climate change, biodiversity loss, and environmental injustice.

By adopting a systems' lens, this study contributes to the growing body of work that seeks to move beyond linear models of growth and exploitation toward regenerative, inclusive, and ecologically grounded solutions. Estuaries serve as a compelling case study, illustrating both the vulnerabilities and potential of complex adaptive systems when managed through a systemic and sustainable approach.

Literature review

The integration of systems theory into ecological and environmental research has gained increasing traction over the past few decades, particularly in the study of complex ecosystems such as estuaries. These transitional zones between freshwater and marine environments are highly dynamic and sensitive to both natural and anthropogenic pressures, making them ideal candidates for a systems-based approach (Paoli et al. 2017; Morales et al. 2022). While foundational works by von Bertalanffy (1968) and Odum (1994) laid the groundwork for applying systems principles to ecological understanding, more recent contributions have emphasized the need to incorporate interdisciplinary frameworks that bridge ecology, economics, and social systems.

Emergy analysis, pioneered by Odum (1996), has proven especially valuable in assessing the sustainability and resilience of estuarine systems. By quantifying all energy flows in solar emjoules, emergy provides a unified metric for evaluating ecosystem services, human impacts, and resource efficiency (Brown and Ulgiati 2016; Morales et al. 2022). Recent studies have extended this methodology to mangrove restoration projects in Southeast Asia (Biswas et al. 2009), oyster aquaculture in the Chesapeake Bay (Williamson et al. 2015), and wetland conservation in China (Su et al. 2020), demonstrating its utility in guiding policy and management decisions.

In addition to technical applications, systems thinking has been increasingly recognized as a critical lens through which to examine global environmental challenges. Meadows (2008) seminal work highlighted how feedback loops, leverage points, and system boundaries influence decision-making and intervention effectiveness. More recent scholarship has expanded on these ideas, emphasizing

the importance of adaptive management and stakeholder engagement in complex socio-environmental systems (Dreiss et al. 2015; Probst and Bassi 2017).

The intersection of systems theory and political economy has also seen growing attention, particularly in relation to critiques of capitalist systems and their role in environmental degradation. McDonnell et al. (2020) argue that the paradox of "sustainable development" within capitalist frameworks often masks continued exploitation of natural resources and marginalized communities. Similarly, Mélenchon's critique of European nationalism and neoliberalism underscores how systemic inequalities exacerbate ecological crises and hinder collective action (Klein 2020).

Recent studies have explored the potential of alternative economic models grounded in degrowth, circular economies, and indigenous ecological knowledge. For instance, Sheinbaum's Fourth Transformation in Mexico offers a promising example of integrating ecological stewardship with social equity and participatory governance (Martínez-Alier et al. 2021). These approaches align closely with the systems thinking framework, advocating for regenerative practices that respect planetary boundaries and prioritize long-term well-being over short-term profit maximization.

Moreover, scholars have increasingly turned to cultural and literary tools to re-engage with ecological values and challenge dominant narratives of growth and exploitation. Roy (2008) and Klein (2020) have called for a resurgence of collective resistance and storytelling as means of reclaiming agency in the face of climate denialism and depoliticization. Literature, in particular, serves as a powerful medium for fostering empathy, envisioning alternative futures, and reconnecting individuals with the broader web of life (Halim 2024; Robinson et al. 2025).

Systems theory and estuarine ecosystems

This section presents the theoretical foundation of systems theory and its relevance to estuarine ecosystems. It explains key concepts such as holism, feedback loops, emergence, and hierarchy, and applies them specifically to estuarine dynamics. Examples include nutrient cycling, predator-prey relationships, and mangrove stabilization.

Introduction to systems theory

Systems theory is an interdisciplinary framework that examines how components within a system interact to produce complex behaviours and outcomes. Originating from the work of Ludwig von Bertalanffy in the mid-20th century, systems theory challenges reductionist approaches by emphasizing the importance of understanding phenomena as integrated wholes rather than isolated parts (Bertalanffy 1968; Hammond 2010). A lens through which to analyse the complex relationships between organisms, their environments, and human activities is provided by systems theory in ecological contexts.

Estuaries, where freshwater rivers meet saltwater oceans, are ideal candidates for systems analysis due to their high degree of complexity, interconnectivity, and sensitivity to environmental change. These transitional zones are influenced by physical, chemical, and biological processes occurring across multiple spatial and temporal scales, making them dynamic and adaptive systems.

Holism and interconnectedness in estuaries

A central tenet of systems theory is holism, the idea that systems must be understood as integrated entities rather than as collections of individual components (Levins and Lewontin 1994). In estuarine systems, holism manifests in the way that changes in one part of the system, such as upstream agricultural runoff, can affect water quality, biodiversity, and sedimentation patterns downstream (Looijen 2012).

For example, nutrient inputs from fertilizers used in agriculture may lead to eutrophication in estuaries, triggering algal blooms and oxygen depletion that threaten fish populations and other aquatic life. A holistic approach enables scientists and managers to trace these effects throughout the system and design interventions that address root causes rather than symptoms.

Feedback loops and system stability

Feedback loops are essential mechanisms that regulate system behaviour and maintain stability or drive change. In estuaries, both positive and negative feedback loops play critical roles in shaping ecosystem dynamics. Negative feedback loops help maintain equilibrium. For instance, wetlands and mangroves act as natural filters, absorbing excess nutrients and stabilizing sediments, which prevents excessive eutrophication and maintains water clarity. Positive feedback loops, on the other hand, amplify disturbances. An example is the overfishing of shellfish, which reduces their capacity to filter water, leading to increased turbidity and reduced light penetration, further degrading water quality.

Understanding these feedback mechanisms allows researchers and policymakers to design management strategies that reinforce stabilizing forces while mitigating destabilizing ones.

Emergence and complexity in estuarine systems

Emergence refers to properties or behaviours that arise at the system level and cannot be predicted by studying individual components alone. In estuaries, emergent properties include high biodiversity, carbon sequestration, and resilience to disturbances.

These characteristics emerge from the interactions among physical factors (e.g., salinity gradients), chemical processes (e.g., nutrient cycling), and biological elements (e.g., species interactions). For instance, the mixing of fresh and salt water creates unique habitats like salt marshes and mudflats, supporting specialized flora and fauna not found elsewhere.

Another hallmark of systems is emergence, where new properties arise at the system level that are absent in individual components. For instance, in estuaries, the high biodiversity and productivity emerge from the complex interactions between freshwater, saltwater, nutrients, and organisms, demonstrating how novel ecological behaviours and patterns can materialize from simple environmental building blocks. For example, Carvalho Junior (2016) has highlighted the importance of the neotropical otter as a controller of carbon stocks in lake, lagoon and estuarine systems in southern Brazil.

Emergent properties are vital for maintaining the functionality and health of estuarine ecosystems. They also highlight the limitations of reductionist approaches, which often fail to capture the full complexity of ecological systems. These emergent characteristics, such as high biodiversity, nutrient cycling efficiency, and resilience to environmental stressors, arise from the dynamic interactions among physical, chemical, and biological components within the system.

Because these properties cannot be predicted solely by studying individual elements in isolation, they underscore the need for holistic, systems-based research and management strategies that account for interdependencies and nonlinear responses. Ignoring this complexity can lead to misguided interventions that disrupt ecosystem balance and reduce long-term sustainability. Therefore, understanding and preserving emergent properties is essential for effective estuary conservation and adaptive management in the face of ongoing environmental change (Likens 1998).

Hierarchy and multi-scale organization

Systems theory also emphasizes hierarchical organization, where smaller subsystems operate within larger ones. In estuarine ecosystems, this hierarchy includes a micro-level represented by individual organisms and microbial communities, meso-level which are the populations and food webs and macro-level that is the entire estuary and its connection to river basins and coastal seas.

This hierarchical structure influences how energy and materials flow through the system and how disturbances propagate across different levels. For example, changes in climate patterns at the global scale can influence sea level rise, affecting sediment transport and habitat availability at the local estuarine level.

By recognizing these multiscale interactions, systems thinking helps ensure that management strategies consider both localized and broader environmental pressures. It enables decision-makers to trace how global phenomena, such as climate change, sea level rise, or ocean acidification, intersect with regional and local stressors like pollution, land-use change, and overfishing. This integrative perspective fosters adaptive and resilient governance, where interventions are not only responsive to immediate challenges but also aligned with long-term ecological integrity and social well-being. As a result, policies can be designed to address root causes rather than symptoms, promoting sustainability across interconnected natural and human systems.

Case application: Mangrove stabilization and resilience

Mangroves provide a compelling example of how systems theory applies to estuarine environments. As foundational species, mangroves stabilize shorelines, reduce erosion, and support diverse marine and terrestrial life.

From a systems' perspective, mangroves interact with tidal flows, sediment deposition, and nutrient cycling. Their root structures trap sediments, reinforcing shoreline stability and promoting further mangrove growth (positive feedback). The collective action of mangroves results in emergent properties such as storm protection and carbon storage. Mangrove forests function as subsystems within larger estuarine and coastal systems.

Restoration projects that apply systems principles have shown greater success by considering these interconnected dynamics rather than focusing solely on replanting trees. By recognizing the complex relationships between hydrology, sediment transport, nutrient cycling, and species interactions, these initiatives move beyond superficial interventions to restore the entire ecological network. For instance, restoring natural water flow patterns and reconnecting floodplains can significantly enhance habitat quality and resilience to climate change. Additionally, incorporating local and indigenous knowledge ensures that restoration efforts align with cultural values and community needs, fostering long-term stewardship. Monitoring and adaptive management further improve outcomes by allowing for adjustments based on how the system responds over time. In this way, systems-based restoration enhances ecological function and supports biodiversity, carbon sequestration, and the well-being of human communities dependent on these ecosystems.

This section has introduced the core principles of systems theory, holism, interconnectedness, feedback loops, emergence, and hierarchical organization, and demonstrated their relevance to estuarine ecosystems. By applying these concepts, we gain a more profound understanding of how estuaries function as complex adaptive systems and how they respond to both natural and anthropogenic pressures. In the next section, we will explore emergy analysis, a systems-based method that quantifies all energy and material flows in terms of solar energy equivalents, offering a unified metric for evaluating estuarine sustainability.

Emergy as a system language to study estuaries

Emergy analysis, developed by Howard T. Odum, offers a powerful systems-based framework for evaluating the complex interactions within estuarine ecosystems. By quantifying all energy and material flows in terms of solar energy equivalents (solar emjoules), emergy provides a unified metric that bridges ecological, economic, and social dimensions. This section explores what emergy is, key concepts such as transformity and yield ratio, its application in estuary studies, and the advantages it brings to understanding and managing these dynamic environments.

What is emergy?

Emergy (spelled with an “m”) is a systems language and analytical tool used to assess the total energy required, directly or indirectly, to produce a good, service, or environmental process. Unlike energy, which measures the capacity to do work, emergy accounts for the quality and transformation history of energy flows. It expresses all inputs to a system in a common unit: solar emjoules (sej), allowing direct comparisons across natural and human-driven processes.

In estuarine systems, emergy helps quantify the energy driving physical processes, such as tides, river flow, and sediment transport; the role of biological productivity, including phytoplankton growth, mangrove development, and fish populations; and the impact of human activities, such as fishing, aquaculture, land reclamation, and pollution.

This integrated approach enables researchers to move beyond fragmented analyses and instead evaluate estuaries as interconnected systems where natural and anthropogenic forces interact.

Transformity and yield ratio

Two fundamental metrics in emergy analysis are transformity and yield ratio, both of which provide insights into the efficiency, sustainability, and value of different components within an estuarine system. Transformity measures how much emergy is required to generate one unit of available energy or material. It reflects the cumulative transformations that occur as energy moves up the food web or through production chains. For example, primary producers like phytoplankton and seagrasses have low transformity, as they directly harness solar energy. On the other hand, higher trophic levels, such as fish and shellfish, have higher transformity, due to the multiple energy conversions required to support their growth.

Understanding transformity helps identify critical species or processes that are especially valuable or vulnerable within the system. In conservation planning, this knowledge can guide efforts to protect high-transformity elements, ensuring long-term ecological resilience.

The emergy yield ratio (EYR) compares the total emergy output of a system to the emergy invested by humans. A high EYR indicates that the system is largely self-sustaining and efficient in generating benefits relative to human inputs. Conversely, a low EYR suggests overexploitation or dependence on unsustainable practices.

For instance, healthy wetlands may have a high EYR because they provide significant ecosystem services (e.g., water filtration, carbon storage) with minimal human investment. Overfished estuaries often show declining EYRs, reflecting diminishing returns from continued resource extraction. These indicators help managers assess the sustainability of estuarine use and guide decisions toward more regenerative practices.

Applications in estuary studies

Emergy analysis has been widely applied to estuarine systems around the world, offering valuable insights into their structure, function, and sustainability. These applications include a mangrove restoration in Southeast Asia. A study by Biswas et al. (2009) evaluated mangrove restoration projects using emergy synthesis. The research revealed how restored mangroves enhance coastal protection, carbon sequestration, and fisheries productivity while also delivering socio-economic benefits. By quantifying renewable and non-renewable inputs, emergy analysis helped identify best practices for sustainable mangrove management.

In Chesapeake Bay oyster aquaculture, Williamson et al. (2015) assessed two oyster farming systems, floating rafts and on-bottom cages, in the Chesapeake Bay. Their emergy evaluation considered all inputs, including tidal energy, organic matter, hatchery products, and human labour. The study found that both systems relied heavily on local renewable resources, but had relatively low environmental impacts compared to other forms of aquaculture.

Su et al. (2020) conducted an emergy-based assessment of wetland conservation in the Liaohe Estuary (China). Using indicators such as the environmental loading ratio (ELR) and yield ratio (YR), the study showed how changes in land use and pollution levels affected emergy flows, offering policy recommendations to reduce stressors and enhance system resilience. These case studies illustrate how emergy analysis supports evidence-based decision-making in estuarine conservation and restoration.

Advantages of emergy analysis

Emergy analysis offers several distinct advantages when applied to estuarine systems, making it a powerful tool for integrating ecological, economic, and social considerations. One is the holistic perspective. Emergy captures the entire spectrum of energy and resource flows within an estuary. By integrating ecological, economic, and social dimensions, it bridges the gap between natural processes and human activities, offering a comprehensive view of system dynamics.

Another advantage is the common currency. All emergy flows are expressed in solar emjoules, enabling direct comparisons across diverse processes and scales. This standardization allows researchers to evaluate trade-offs, identify dominant energy sources, and prioritize actions that enhance system health. For example, solar radiation driving primary production can be directly compared to fossil fuel-based inputs from upstream agriculture. Furthermore, renewable energy contributions from tidal flows can be weighed against non-renewable pollution loads.

Sustainability focus can be addressed as emergy distinguishes between renewable and non-renewable resources, highlighting the extent to which a system relies on sustainable energy sources versus unsustainable human interventions. This focus helps identify practices that deplete natural capital, such as overfishing or habitat destruction, and encourages strategies that promote long-term viability.

Emergy analysis is highly scalable (scalability), applicable at local levels, such as analysing the energy dynamics of a single estuary, or expanded to global scales, such as assessing the role of estuaries in Earth's broader biogeochemical cycles. This flexibility makes it suitable for guiding localized restoration projects or informing international policies aimed at protecting estuarine systems as vital components of planetary health.

Emergy provides objective, science-based metrics that support informed policy and management decisions (police and management support). It enables stakeholders to balance economic development with environmental protection, ensuring that estuarine systems remain resilient and productive for future generations.

Therefore, emergy analysis serves as a robust systems language for studying estuaries, offering a holistic, standardized, and scalable method for understanding complex interactions among natural and human-driven processes. Through metrics such as transformity and yield ratio, it reveals the sustainability and efficiency of estuarine functions. Applied in real-world contexts, from mangrove restoration to aquaculture, it provides actionable insights that inform conservation, management, and policy development.

In the next section, we will explore key principles of systems theory and how they apply specifically to estuarine ecosystems, further strengthening the systems-based understanding of these vital environments.

Case studies in systems thinking and estuary management

To illustrate the practical application of systems thinking and emergy analysis, this section presents three real-world case studies that demonstrate how these tools can guide sustainable estuary management. These cases highlight diverse applications across geographic and cultural contexts, showing how integrated frameworks can inform ecological restoration, conservation, and policy

development. Each case includes context and problem description, systems challenges and feedback mechanisms, emergy-based evaluation, lessons learned and policy implications.

Herring River Estuary restoration (Cape Cod, USA)

The Herring River Estuary, located in Cape Cod, Massachusetts, has undergone significant ecological degradation due to historical tidal restrictions. In the early 20th century, a dike was constructed to drain wetlands for mosquito control and land development, severely limiting tidal exchange. This led to salt marsh loss, reduced biodiversity, and increased vulnerability to sea level rise.

Restoration efforts began in the early 2000s, led by the National Park Service, with the goal of restoring natural hydrology and ecosystem function while balancing community concerns related to flooding and infrastructure impacts. One of the primary systems challenges was understanding the cascading effects of restricted tidal flow on water quality, sedimentation, and habitat availability. Feedback loops were instrumental, as the negative feedback from wetland vegetation that had previously stabilized sediments and buffered storm surges was now a significant factor. Decreased tidal flushing was linked to positive feedback, which further degraded habitat by increasing salinity stratification, lowering oxygen levels, and increasing methane emissions. These dynamics underscored the need for an adaptive, systems-based approach that could account for nonlinear responses to restoration actions.

An emergy assessment conducted as part of the planning process revealed the high value of natural tidal flows in maintaining system resilience (Dreiss et al. 2015). The study quantified renewable inputs such as solar radiation and tidal energy, non-renewable inputs from human interventions (e.g., construction, monitoring), and ecosystem services including carbon sequestration, fish nursery functions, and flood protection.

Emergy indices such as the Environmental Loading Ratio (ELR) and Yield Ratio (YR) were used to compare different restoration scenarios. Results indicated that restoring tidal connectivity significantly improved the ratio of renewable to non-renewable inputs, enhancing overall sustainability.

Key lessons from the Herring River restoration include the importance of adaptive management in complex systems where outcomes are uncertain, the value of emergy analysis in evaluating trade-offs between short-term costs and long-term benefits, as well as the need for stakeholder engagement to align ecological goals with social and infrastructural needs. Policy recommendations emphasize integrating systems thinking into coastal zone planning and using emergy metrics to guide investment decisions. This case illustrates how systems approaches can support large-scale ecological restoration while addressing climate change adaptation.

Mangrove restoration in Southeast Asia

Mangroves in Southeast Asia have been extensively deforested over the past several decades due to aquaculture expansion, urbanization, and timber harvesting. Countries like Thailand, Vietnam, and Indonesia have lost significant mangrove cover, leading to increased coastal erosion, loss of biodiversity, and

diminished livelihood opportunities for local communities. In response, governments, and NGOs have initiated mangrove restoration projects aimed at reversing these trends and enhancing coastal resilience.

As mangrove ecosystems are highly dynamic and interdependent, key systems challenges included the re-establishing hydrological connectivity after years of drainage and balancing local livelihood requires with ecological restoration goals. Managing feedback loops that influence success were the positive feedback related to healthy mangroves that trap sediments and nutrients, promoting further growth and stability. Negative feedback was related to degraded areas that suffer from erosion, making replanting efforts less effective without initial stabilization. Understanding these interactions was essential for designing site-specific interventions that supported long-term recovery.

An emergy synthesis study (Biswas et al. 2009) assessed mangrove restoration projects in Southeast Asia. It compared restored sites with degraded ones and found that restored mangroves had higher renewable emergy inputs, particularly from tidal flows and organic matter accumulation. Also, they provided greater ecosystem service values, including carbon storage, shoreline protection, and fisheries enhancement. Finally, emergy indicators highlighted the importance of minimizing non-renewable inputs (e.g., external funding, imported seedlings) to ensure long-term viability. The study also emphasized the socio-economic co-benefits, including ecotourism and sustainable fishing opportunities, which contributed to community buy-in and project sustainability.

Important insights from mangrove restoration efforts include that the community involvement is crucial for ensuring project longevity and effectiveness. Site suitability assessments should precede planting to avoid failures due to poor hydrology or salinity. Emergy-based planning supports cost-effective, scalable restoration strategies. Policymakers are encouraged to incorporate systems principles and emergy metrics into national environmental policies and coastal development plans. Integrating ecological restoration with poverty reduction and climate adaptation strategies can yield multiple benefits across sectors.

Liaohe estuary wetland conservation (China)

The Liaohe Estuary, located in northeastern China, is one of the country's most significant wetland ecosystems. Historically rich in biodiversity, it has faced increasing pressure from industrial development, agricultural runoff, and oil extraction activities. These pressures have led to habitat fragmentation, pollution, and declining water quality.

In response, the Chinese government launched a comprehensive conservation program focused on protecting and restoring critical wetland habitats, especially those supporting migratory bird populations and rare species like the red-crowned crane (*Grus japonensis*).

The Liaohe Estuary is embedded within a larger socio-environmental system that includes upstream agriculture, coastal industry, and urban centres. Challenges included interconnected water use and pollution from upstream sources and competition for land use between conservation and economic development. There was also a complex feedback dynamic to be, managed.

The negative feedback from pollution and habitat loss that reduced biodiversity and ecosystem services. The positive feedback from wetland restoration that enhanced filtration capacity and stabilized shorelines. Addressing these issues required a coordinated, cross-sectoral approach rooted in systems thinking.

A recent emergy analysis (Su et al. 2020) evaluated the sustainability of wetland conservation efforts in the Liaohe Estuary. Findings included high transformity values in restored wetlands that indicated their ecological importance and resource efficiency, increased renewable emergy inflows (e.g., solar radiation, rainfall) that supported greater biodiversity and carbon sequestration, and lower environmental loading ratios (ELR) in protected zones that demonstrated reduced stress from human activity.

The study concluded that emergy-based evaluations could help prioritize conservation zones and optimize resource allocation. This includes policy implications such as integrated watershed management, essential for addressing root causes of degradation. The emergy metrics offered a powerful tool for guiding conservation investments and measuring outcomes. Cross-agency collaboration is necessary to manage land-sea interactions effectively.

Policy recommendations included: expanding protected areas and enforcing buffer zones around sensitive habitats, promoting green infrastructure solutions like constructed wetlands, and incorporating systems indicators into national environmental performance assessments. This case demonstrates how systems thinking and emergy analysis can support large-scale conservation in densely populated, economically active regions.

These three case studies, Herring River Estuary Restoration (USA), Mangrove Restoration in Southeast Asia, and Liaohe Estuary Wetland Conservation (China), illustrate the power of systems thinking and emergy analysis in guiding sustainable estuary management. Each case reveals how feedback mechanisms, emergy flows, and stakeholder engagement shape restoration outcomes. By applying these tools, policymakers and practitioners can design interventions that enhance ecological resilience, support local communities, and align with broader sustainability goals.

Youngsan River (Korea)

Kang (2013) applies emergy analysis to evaluate the contributions of the Youngsan River Estuary ecosystem to the Korean economy, quantifying its ecological and economic value. By converting all inputs, such as energy flows, material resources, and monetary investments, into a common metric of solar emjoules (sej), the study provides a holistic assessment of the ecosystem's functions, including water purification, habitat provision, and scientific research. Key emergy indices, such as the unit emergy value (UEV) and solar emergy, are calculated to assess the system's sustainability and economic significance. While the study highlights the estuary's critical role in supporting ecological and economic systems, it acknowledges limitations, such as reliance on foreign data for UEV calculations and challenges in quantifying scientific research contributions. Despite these constraints, the analysis underscores the importance of integrating ecological and economic perspectives to inform sustainable management and policy decisions for the estuary.

Mai Po mangrove (Hong Kong)

An emergy evaluation of the Mai Po mangrove marshes showed that emergy analysis is useful in quantifying ecological and economic contributions (Qin et al. 2000). By converting all energy inputs, such as renewable resources (e.g., sunlight, tidal flows), non-renewable resources (e.g., organic matter), and human investments (e.g., shrimp farming), into a common metric of solar emjoules (sej), the study provides a holistic assessment of the system. Key findings include a total output emergy of 26.39×10^{17} sej/year, with emergy indices such as the investment ratio (IR = 0.48), environmental loading ratio (ELR = 1.03), and yield ratio (YR = 3.10), which reflect the balance between economic activities and environmental sustainability. The analysis also highlights the marshes' significant ecological functions, including habitat provision for migratory birds and shrimp production, as well as their educational value, estimated at 125.65 $\times 10^{17}$ sej/year. This application of emergy analysis underscores its ability to integrate ecological and economic dimensions, offering actionable insights for sustainable management and policy development in mangrove ecosystems.

Principles of system's theory

Systems theory provides a foundational framework for understanding how systems function, transform, and interact with their environment. These principles highlight the dynamic nature of systems and their ability to adapt, store resources, and regulate themselves through feedback mechanisms. This section outlines four key principles: transformation of Inputs, energy-material-information requirements, storage and structure, and feedback reinforcement. Each principle is explained in detail, with examples relevant to estuarine systems to illustrate how these concepts apply in real-world contexts.

Transformation of inputs

At its core, a system transforms inputs into outputs. All systems, whether natural or human-made, take in energy, materials, and information from their surroundings and convert them into useful products or services. Inputs may include energy (sunlight, tidal forces, electricity), materials (nutrients, water, raw resources) and information (data, genetic instructions, policy directives) (Fig. 1).

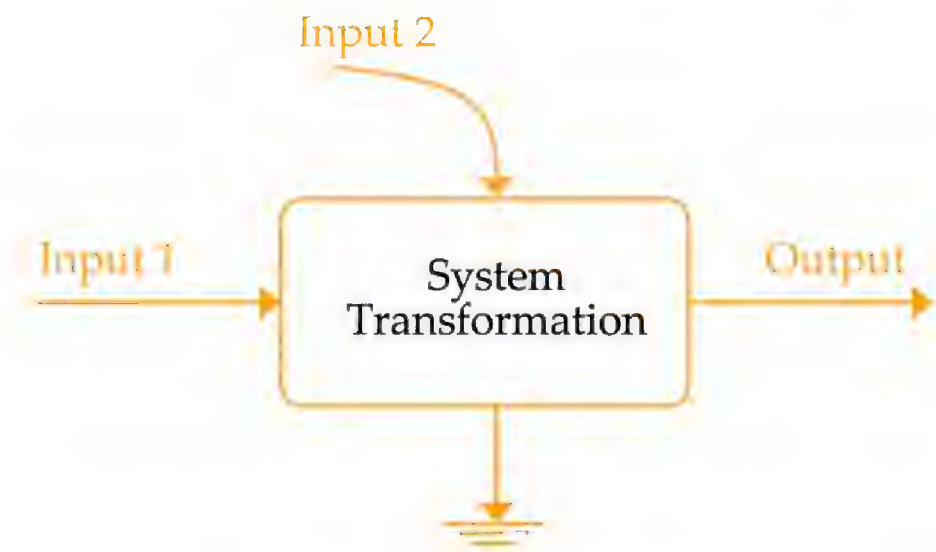


Figure 1. The first principle of systems theory defines the system as an entity that transforms inputs into outputs.

Within the system, these inputs undergo various processes of transformation to produce outputs, which can be physical (e.g., biomass), energetic (e.g., heat), or informational (e.g., ecological signals). For example, in an industrial factory, raw materials are transformed into finished goods using energy and labour. In an estuary ecosystem, solar energy drives photosynthesis, converting carbon dioxide and water into organic matter, which supports food webs and biodiversity.

This principle underscores that systems are not static but are constantly engaged in the flow and transformation of resources, making them dynamic and adaptive entities.

Energy-material-information requirements

Every transformation within a system requires three essential inputs: energy, materials, and information. These inputs work together to enable the system to function effectively. Energy is the driving force behind all transformations. It powers the processes that convert inputs into outputs. In an estuary, solar energy fuels biological productivity. Nutrients from river runoff support the growth of phytoplankton and aquatic plants. Decomposers like bacteria and fungi break down detritus, recycling nutrients back into the system (Fig. 2).

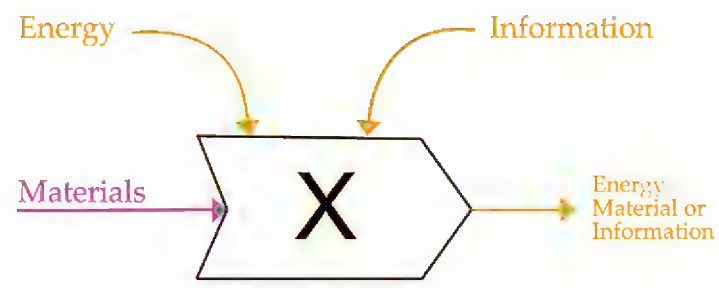


Figure 2. The second principle of systems theory states that every transformation within a system requires three essential inputs: energy, materials, and information.

Materials provide the physical components necessary for transformations. They are the building blocks of outputs. In an estuary, nutrients, sediments, and organic matter serve as material inputs that sustain mangroves, seagrasses, and fish populations. In a city, construction materials, water, and fuel are essential for infrastructure and daily operations.

Information guides how energy and materials are used. It includes rules, instructions, and feedback that direct system behaviour. In an estuary, genetic information determines how species such as mangroves, oysters, and fish adapt to their unique environment. Ecological feedback mechanisms regulate population dynamics and nutrient cycles.

Without these three inputs working in concert, transformations cannot occur, emphasizing the critical interdependence of energy, materials, and information in all systems.

Storage and structure

In addition to transforming inputs, systems also store resources to ensure stability and resilience over time. High-quality storages allow systems to buffer against fluctuations and maintain functionality even when external conditions change.

Systems accumulate and store material, energy and information. Material storages can be soil storing nutrients, reservoirs storing water, and banks

storing financial reserves. Examples of energy storages are chemical energy stored in plant biomass, batteries storing electricity, and detritus storing organic matter in estuaries. Information storages are represented by DNA storing genetic instructions, digital databases storing knowledge, and cultural memory preserving traditions (Fig. 3).

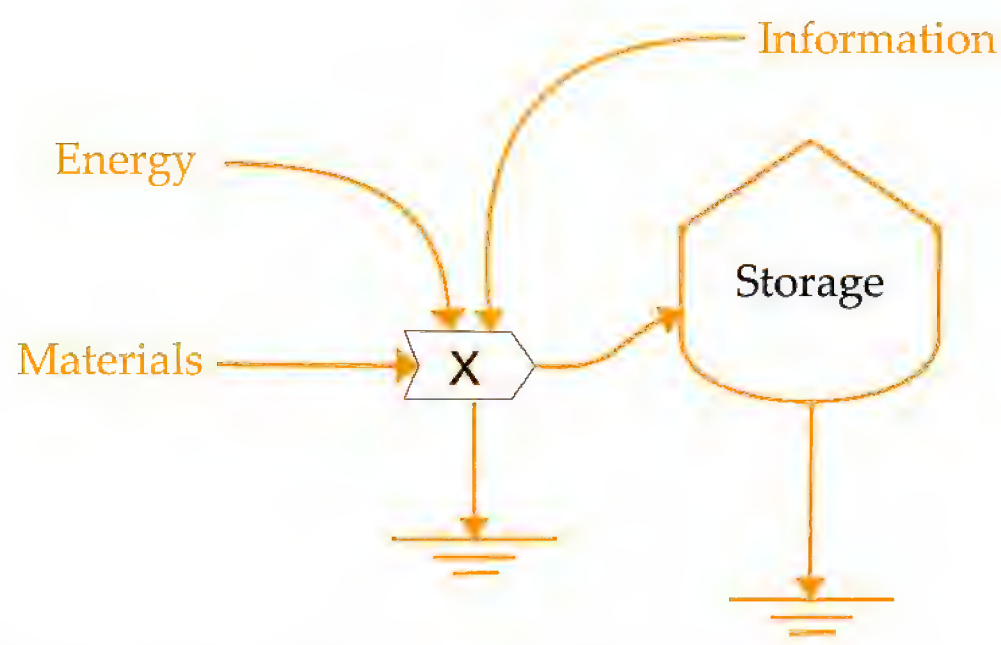


Figure 3. Systems store resources to ensure stability and resilience.

These storages are crucial because they allow systems to operate smoothly during periods of scarcity or stress. For example, during low-nutrient seasons, estuarine systems rely on stored organic matter to support food webs. Mangrove forests store carbon in biomass and soils, helping mitigate climate change while maintaining habitat integrity. Understanding storage mechanisms helps researchers and managers design systems that are more resilient, efficient, and capable of withstanding disruptions.

Feedback reinforcement

Feedback loops are central to how systems regulate themselves and respond to changes. A main property of systems is the use of high-quality storages in positive feedback actions to amplify desired outcomes or stabilize the system (Fig. 4).

Positive feedback loops reinforce changes by amplifying certain behaviours or processes. In ecosystems, healthy populations of keystone

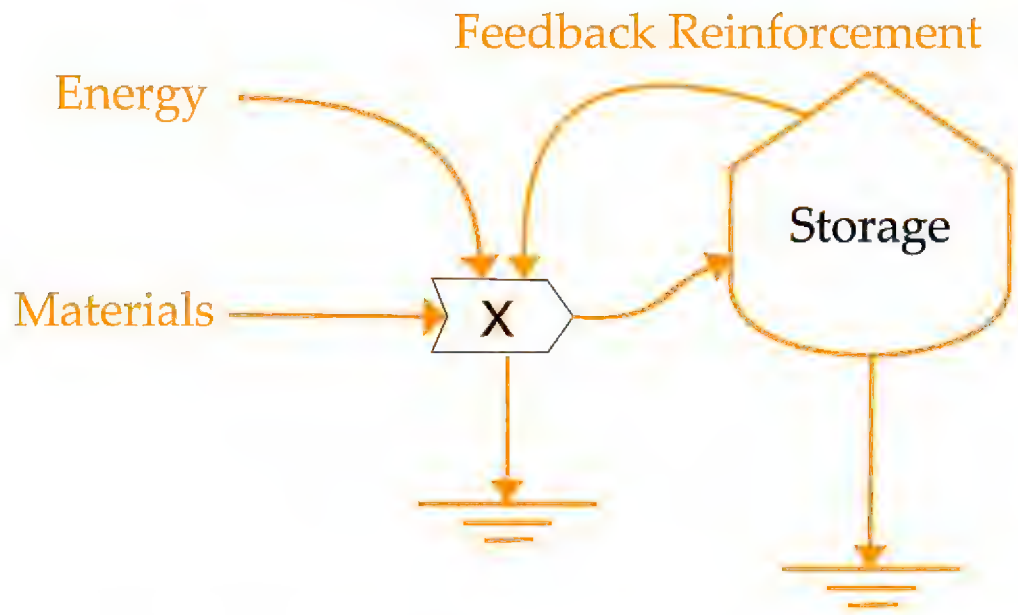


Figure 4. Feedback loops are central to how systems regulate themselves and respond to changes.

species (e.g., predators or pollinators) can trigger positive feedback loops that enhance biodiversity and ecosystem resilience. In social systems, successful innovations can create exponential growth by attracting more users, funding, or adoption.

For example, restoring wetlands in an estuary can lead to increased filtration capacity, improved water quality, and enhanced fish habitats, which in turn attract more investment in conservation.

Negative feedback loops, on the other hand, stabilizes systems by counteracting deviations and maintaining balance. In an estuary, wetlands and mangroves absorb excess nutrients and stabilize sediment, preventing excessive eutrophication. In economies, regulatory policies act as negative feedback by curbing inflation or environmental degradation.

By leveraging high-quality storages, such as capital, biodiversity, or knowledge, systems can reinforce both types of feedback to maintain equilibrium or drive transformation.

The four principles of systems theory, the transformation of inputs, the requirement of energy, materials, and information, the development of high-quality storages, and the use of feedback reinforcement, collectively illustrate how systems function as dynamic, interconnected entities.

These principles emphasize the importance of understanding systems holistically, recognizing the interplay between energy flows, material cycles, and informational guidance. By applying these principles, we can better design sustainable systems, manage complex challenges, and foster resilience in both natural and human-made environments.

System design and emergy modelling

Emergy analysis provides a powerful framework for modelling complex systems by quantifying all energy and material flows in solar emjoules. This approach enables researchers to visualize, interpret, and evaluate the structure and function of ecosystems such as estuaries.

In this section, we explore how to construct and interpret emergy models using Howard T. Odum's energy systems language, apply these tools to a real-world example, the Araranguá River Estuary, and explain how to analyse the flows and storages that shape system dynamics.

Diagramming systems using Odum's energy systems language

Howard T. Odum developed a unique symbolic language to represent the structure and function of ecological and economic systems. His energy systems language allows researchers to map out inputs, transformations, storages, and outputs in a visual format that reveals patterns of flow and interaction.

Using these symbols, researchers can create system diagrams that illustrate how energy and resources move through an ecosystem. These diagrams are not just artistic representations, they are functional tools that help identify where energy is stored, how flows interact, which components are most critical, and where interventions may yield the greatest impact.

For example, in an estuary, a system diagram might show solar energy driving photosynthesis, nutrient flows supporting plankton and fish populations,

Table 1. Example of key symbols in Odum's Systems Language.

Symbol	Meaning
	Solar energy input
	Energy source
	Consumer
	Producer
	Storage (e.g., biomass, nutrients)
	Switch
	Transaction
	Interaction or transformation process
	Dissipation or entropy

human activities like fishing or pollution altering natural cycles, and wetlands acting as storage zones that regulate water quality. By applying this symbolic language, emergy models become both scientifically rigorous and visually intuitive, enabling better communication among scientists, policymakers, and stakeholders.

Application to Araranguá River Estuary

The Araranguá River Estuary, located in southern Brazil, serves as an excellent case study for emergy-based system design. It is a dynamic environment influenced by freshwater inflows, tidal movements, and human activity such as aquaculture and land use change.

Step 1: Defining the system boundary

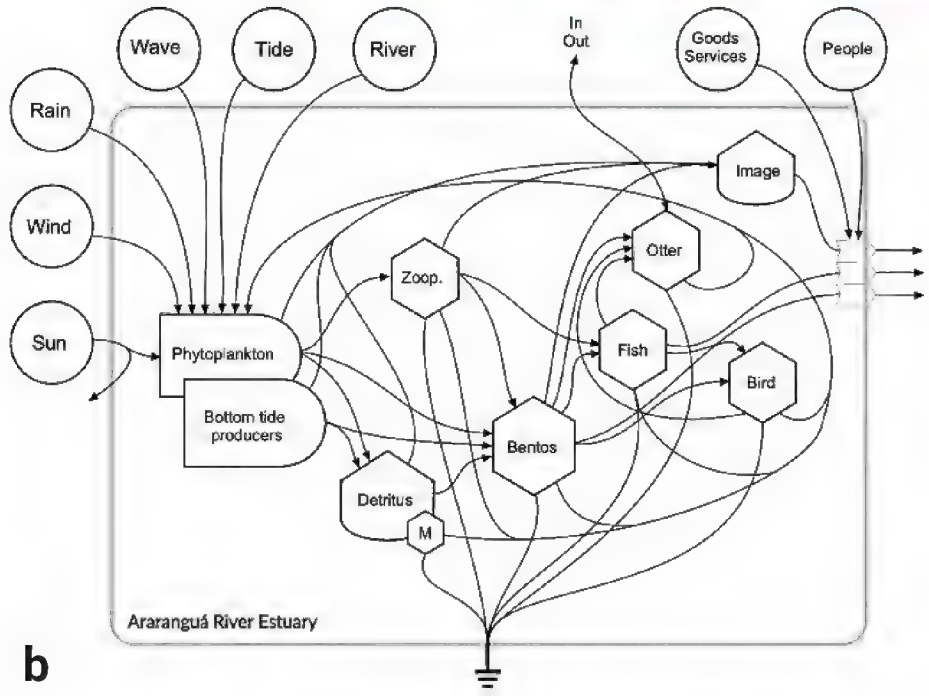
To model the estuary effectively, it is essential to define the system boundary, what is included and excluded from the analysis. In this case, the boundary includes freshwater inflows from the Araranguá River, tidal exchanges with the Atlantic Ocean, biological productivity (phytoplankton, mangroves, fish), and human activities (fishing, agriculture, urban development). This ensures that both natural and anthropogenic influences are captured in the model.

Step 2: Constructing the system diagram

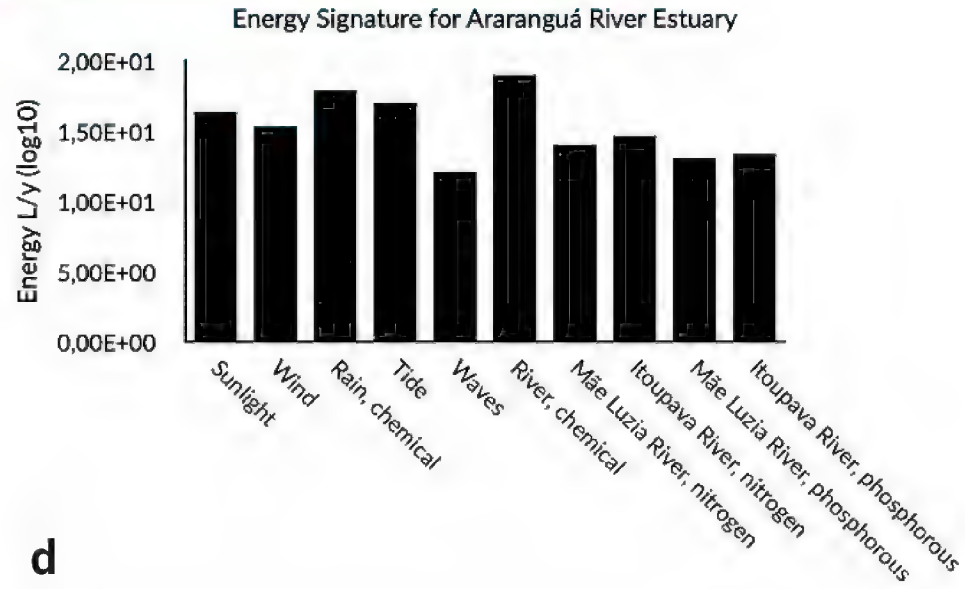
Using GIS data and field observations, a base map of the estuary was created (Fig. 5a). This was then translated into a system diagram using Odum's energy systems language (Fig. 5b), showing key elements and interactions. Fig. 5c is the mathematical representation of the second (5b), quantifying the main elements of the system based on emergy calculations. Fig. 5d is a refinement or product of the third (5c), assigning an identity to the system to facilitate its monitoring and management.

This layered approach allows for increasing levels of detail and precision, making it possible to move from observation to quantification and ultimately to informed decision-making.

a



b



d

Note[a]	Item	Raw data	Transformity[b] (sej/J)	Solar Emergy seJ/yr	PIB Brazil 2023	Emvalue, Reals
1	Sunlight	2,26E+16	1	2,26E+16	1,09E+13	R$ 2.070,11
2	Wind	9,85E+11	2.450	2,41E+15	1,09E+13	R$ 221,36
3	Rain, chemical	2,79E+13	30.500	8,50E+17	1,09E+13	R$ 77.936,28
4	Wave	2,61E+07	51.000	1,33E+12	1,09E+13	R$ 0,12
5	Tide	1,48E+12	73.900	1,09E+17	1,09E+13	R$ 10.023,84
6	River. chemical	1,27E+14	81.300	1,03E+19	1,09E+13	R$ 947.117,72
7	Mãe Luzia River, nitrogen	2,61E+04	4,19E+09	1,10E+14	1,09E+13	R$ 10,05
8	Itoupava River, nitrogen	1,15E+05	4,19E+09	4,82E+14	1,09E+13	R$ 44,18
9	Mãe Luzia River, phosphorous	8,29E+02	1,4E+10	1,16E+13	1,09E+13	R$ 1,06
10	Itoupava River, phosphorous	1,78E+03	1,4E+10	2,50E+13	1,09E+13	R$ 2,29
	Image			1,13E+19		
	Total			1,13E+19		1,04E+06

c

Figure 5. Emergy Model of the Araranguá River Estuary. **a.** Base map derived from satellite imagery. **b.** Conceptual diagram using Odum's symbols to represent system components and flows. **c.** Quantified emergy values assigned to each component. **d.** Final model used for monitoring and management.

Step 3: Assigning emergy values

Each element in the diagram was assigned an emergy value, expressed in solar emjoules (sej), based on field measurements and literature sources (Fig. 5c). For instance: wind contributes approximately 2.41E+15 seJ/yr, tidal flows provide significant renewable energy (1.09E+13 seJ/yr), human inputs such as agricultural runoff and aquaculture were quantified and compared against natural flows. These values allow for direct comparisons between different types of inputs and help assess the sustainability of the system.

Interpretation of flows and storages

Once the model is built and emergy values are assigned, the next step is to interpret the flows and storages within the system. This interpretation helps identify where energy is being efficiently used or wasted, how storages contribute to system resilience, and the role of feedback mechanisms in maintaining stability.

To understand key components, let's break down a simplified consumer-level diagram (Fig. 6), representing a fish or river otter in the estuary. To complete the figure, we need to identify and label the elements, interactions, storage, and entropy within the system.

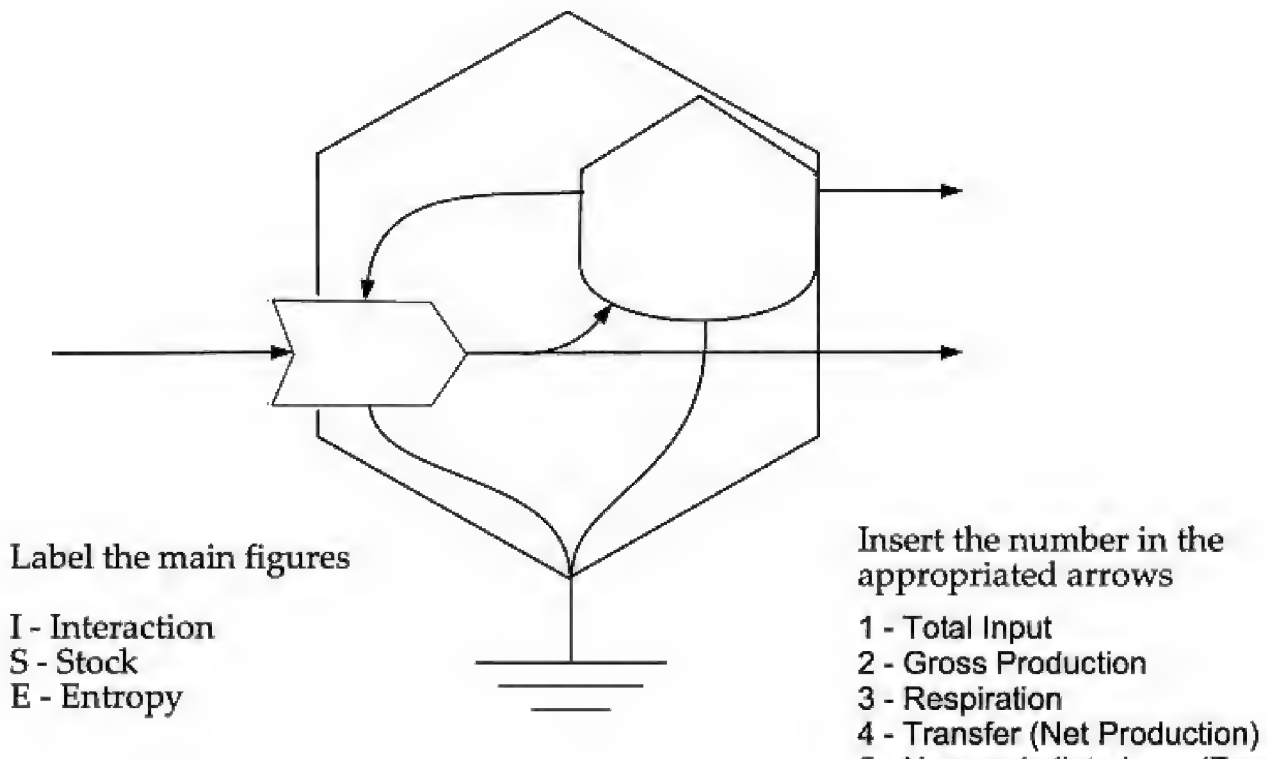

Label the main figures
I - Interaction
S - Stock
E - Entropy
Insert the number in the appropriated arrows
1 - Total Input
2 - Gross Production
3 - Respiration
4 - Transfer (Net Production)
5 - Non-assimilated use (Egestion)

Figure 6. Representation of a Consumer in the Estuarine System. I – Input: Represents the total energy entering the organism, such as food intake or detritus consumption. S – Stock/Storage: Refers to the accumulation of energy within the organism (e.g., fat reserves, muscle tissue). E – Entropy: Shows the dissipation of energy as waste or heat during metabolic processes.

Now we can assign numbers to flows. The arrows in the diagram correspond to different types of energy flow. Total Input (1) is the primary inflow of energy or materials (e.g., food). Gross Production (2) represents the total energy transformed internally (e.g., digestion, metabolism). Respiration (3) means the energy used for maintenance and survival. Net Production (4) is the usable output for growth and reproduction, and non-assimilated Use (5) the waste expelled (e.g., feces, urine). These flows help quantify the efficiency of energy transfer and reveal potential points of intervention or vulnerability.

A complete system diagram also includes elements (nodes), physical or abstract components such as rivers, mangroves, and fisheries. Interactions (arrows) show how energy and materials move between elements. Purpose, or function, defines the system's goal. In the case of the estuary, it may include biodiversity support, carbon sequestration, tourism, or provision of ecosystem services.

For example, the elements and interactions in Fig. 5b. Elements are rivers, tidal zones, mangroves, fish, sediment, nutrient inputs, human activities (e.g., fishing, shipping). The interactions are represented by river flow bringing sediments and nutrients into the estuary, tidal forces mixing fresh and saltwater, fish migration between zones, and decomposers breaking down organic matter. The purposes or functions are to support biodiversity, filter pollutants, provide nursery habitats, and stabilize shorelines.

By tracing these relationships, researchers can identify leverage points, places where small changes can lead to large-scale improvements, and develop strategies that align with the system's natural functions. These leverage points often exist at critical intersections where interventions can disrupt negative feedback loops, enhance resilience, or redirect the system toward more sustainable trajectories. For example, in estuarine ecosystems, restoring wetlands or reconnecting floodplains can significantly improve water filtration, reduce erosion, and enhance habitat quality for aquatic species. Such interventions address immediate ecological concerns and provide co-benefits such as carbon sequestration and flood protection for nearby human communities.

Moreover, understanding these interconnections allows for the design of adaptive management strategies that respond dynamically to changing conditions, ensuring long-term effectiveness. This systems-informed approach encourages collaboration across disciplines and sectors, fostering integrated solutions that respect both ecological limits and human needs. Ultimately, identifying and acting upon these leverage points enables a shift from reactive problem-solving to proactive stewardship, supporting the regeneration of ecosystems and the sustainability of the services they provide.

System design and emergy modelling offer a structured, visual, and quantitative way to understand estuarine ecosystems. By applying Odum's energy systems language, constructing diagrams grounded in empirical data, and interpreting flows and storages, we gain valuable insights into how estuaries function and how they can be sustainably managed.

The Araranguá River Estuary demonstrates how emergy modelling can translate complex ecological processes into actionable knowledge. Through this approach, managers and policymakers can make decisions that enhance resilience, optimize resource use, and promote long-term sustainability.

Reflections on systems thinking, capitalism, and sustainability

As we conclude our exploration of systems thinking in the context of estuarine ecosystems, it becomes essential to reflect on the broader philosophical and political implications of this perspective, particularly its relationship with capitalism, sustainability, and cultural narratives. Systems thinking challenges dominant paradigms by emphasizing interconnectedness, regeneration, and long-term resilience, which often stand in contrast to the linear, growth-oriented logic of capitalism.

This section explores these tensions and offers reflections on how systems thinking can inform alternative economic models, cultural re-engagement, and future directions for sustainable governance. It highlights how dominant economic paradigms—rooted in capitalist assumptions of endless growth and resource exploitation—are increasingly at odds with the ecological realities of a finite planet. Systems thinking challenges these paradigms by emphasizing interconnectedness, regeneration, and long-term resilience, offering a foundation for alternative models such as degrowth, circular economies, and bioeconomics that prioritize ecological balance and human well-being over profit maximization.

Systems thinking vs. capitalist reductionism

At the heart of the tension between systems thinking, and contemporary economic systems lies a fundamental conflict in worldview and values. Capitalism, as it has evolved over the past few centuries, operates largely on principles of reductionism, competition, and infinite growth. It treats nature as a resource to be extracted, commodified, and consumed, often ignoring the ecological limits and feedback loops that sustain life. This mindset has led to widespread environmental degradation, social inequality, and ecological overshoot.

Systems thinking in China is rooted in a holistic approach deeply influenced by traditional philosophy. At the end of the 20th century, Qian Xuesen played a transformative role in advancing systems thinking within China by synthesizing modern scientific principles with the philosophical traditions of Confucianism, Taoism, and Buddhism (Pan et al. 2013). His work emphasized holism, mutual dependence, and the dialectical unity of reductionism and holism, creating a unique framework for understanding complex problems. These philosophies, which stress unity, harmony, and interdependence, provided distinct insights that enriched the systems perspective (Xu and Gu 2022). By integrating these traditions, Qian developed a uniquely Chinese approach to addressing interconnected challenges, offering a comprehensive and adaptive framework for tackling the complexities of modern systems.

One of Qian Xuesen's most significant contributions to systems theory was his articulation of systems thinking as a dialectical unity of reductionism and holism (Ming 2014). While Western systems thinking often oscillates between these two approaches, Qian proposed integrating them into a cohesive framework. Qian argued that neither approach alone was sufficient. Instead, he advocated for a dialectical synthesis that combines the analytical rigor of reductionism with the integrative vision of holism. In practice, this meant using reductionist tools to understand specific aspects of a system while maintaining a holistic perspective to guide overall strategy. For example, in managing an estuary, one might use reductionist methods to study nutrient flows or sediment transport but apply holistic thinking to design policies that integrate ecological, economic, and social considerations.

In contrast, systems thinking presents a regenerative, holistic worldview that recognizes the interdependence of all components within a system, whether ecological, economic, or social (Ackoff 1994). It emphasizes the feedback mechanisms that regulate balance and stability, the emergent properties that arise from cooperation and complexity, and the hierarchical organization that integrates local actions with global impacts.

These principles challenge the capitalist assumption that wealth can be endlessly accumulated without regard for natural boundaries. As Donella Meadows (2008) reminds us, "Systems cannot be managed. They can only be disturbed." In other words, interventions must align with the system's own dynamics, not override them for short-term gain.

Alternative economic models: Degrowth, circular economies, and indigenous knowledge

Given the unsustainable trajectory of current economic systems, scholars, and policymakers, have increasingly turned to alternative frameworks that better align with systems principles and sustainability goals. The degrowth movement proposes a deliberate reduction in material throughput and consumption, prioritizing well-being, equity, and ecological health over GDP growth. It advocates for local economies, reduced work hours, and sufficiency-based living, offering a compelling critique of growth-as-progress narratives.

A circular economy seeks to eliminate waste by designing systems where materials are reused, recycled, and reintegrated. Inspired by natural cycles, this model reflects key systems principles such as feedback loops, storages, and transformation of inputs, making it a promising framework for sustainable development. Indigenous ecological knowledge is also an interesting alternative being discussed.

Many indigenous cultures have long practiced forms of systems-based stewardship, rooted in reciprocity, respect for nature, and intergenerational responsibility. These approaches emphasize living within ecological limits, maintaining biodiversity, and fostering community resilience, ideas that resonate deeply with systems thinking.

The work of Claudia Sheinbaum in Mexico's Fourth Transformation (4T) provides a modern example of integrating ecological values into governance. Her administration has emphasized renewable energy transitions, conservation policies, and participatory democracy, illustrating how systemic change can align economic priorities with ecological and social well-being.

Cultural re-engagement: Literature and storytelling as tools for change

Beyond economics and policy, systems thinking also calls for a cultural shift, one that reconnects individuals with the natural world and fosters collective responsibility. Writers like Naomi Klein and Arundhati Roy have been instrumental in framing climate change not just as an environmental crisis, but as a social, political, and moral emergency. Their works highlight how marginalized communities bear the brunt of environmental destruction, while calling for radical solidarity, grassroots resistance, and reimagined futures.

Klein's concept of "climate justice" underscores the need to address inequality and colonial legacies in climate action. Similarly, Roy's writings urge us to see activism not as protest, but as a profound act of storytelling and reclaiming agency. Literature plays a crucial role in shaping our understanding of the world and our place within it. Authors like Amitav Ghosh (The Great Derangement) and Kim Stanley Robinson (New York 2140) use fiction to explore climate futures, urging readers to envision alternatives and confront uncomfortable truths.

Storytelling, both fictional and documentary, helps bridge the gap between scientific knowledge and public awareness. It fosters empathy, imagination, and emotional connection, vital tools in mobilizing collective action for sustainability. Through compelling narratives, complex environmental issues, such as climate change, biodiversity loss, or estuarine degradation, can be translated into relatable experiences that resonate with diverse audiences. Whether through novels, films, oral traditions, or digital media, storytelling has the power to humanize data, making abstract concepts tangible and urgent. This cultural practice not only educates but also inspires individuals to see themselves as part of a larger ecological whole, encouraging a sense of responsibility and agency.

The role of systems thinking in future governance

For systems thinking to become more than a conceptual tool and translate into real-world impact, it must influence governance structures, policy design, and decision-making processes. Governments and institutions often operate through fragmented, siloed approaches, which fail to account for the interconnected nature of today's challenges, from climate change to food security, from biodiversity loss to urban resilience.

Integrating systems thinking into governance means adopting cross-sectoral collaboration across the environment, health, economy, and education sectors. It also depends on designing adaptive policies that respond to changing conditions and emerging knowledge and using emergy analysis and systems indicators (e.g., yield ratio, transformity, environmental loading ratio) to guide decisions grounded in ecological reality.

Jean-Luc Mélenchon's critiques of European nationalism and neoliberalism offer a cautionary tale about the dangers of retreating into divisive ideologies at a time when global cooperation and systems-based solutions are urgently needed. His vision, though politically contentious, highlights the importance of solidarity, transparency, and ecological literacy in reshaping political discourse.

By embedding systems thinking into education, media, and public policy, societies can cultivate a new generation of leaders and citizens capable of navigating complexity and designing regenerative futures. Educational institutions can integrate systems principles into curricula across disciplines, helping students understand the interconnected nature of ecological, economic, and social challenges. Media platforms can play a pivotal role by framing issues through a systemic lens, promoting narratives that highlight interdependence, long-term consequences, and holistic solutions. Public policies informed by systems thinking can move beyond short-term fixes to address root causes, fostering resilience and sustainability in governance.

This shift encourages collaboration across sectors, bridging scientific knowledge with community wisdom to create inclusive, adaptive strategies. Moreover, it empowers individuals to see themselves as active participants within larger systems, inspiring a sense of responsibility and agency in shaping a more just and sustainable world. Ultimately, embedding systems thinking across society lays the foundation for transformative change, one that aligns human progress with ecological integrity and social well-being.

Toward a regenerative future

Ultimately, systems thinking invites us to reimagine progress, shifting from a focus on growth and accumulation to one centred on resilience, regeneration, and equity. This requires moving beyond GDP as the primary measure of success, valuing non-market contributions such as ecosystem services and unpaid care work, and recognizing the rights of nature, as seen in legal frameworks adopted in Ecuador and New Zealand. Estuaries, with their rich interdependencies and sensitivity to external pressures, serve as powerful metaphors for the kind of interconnected, adaptive, and responsive governance we must adopt globally.

This reflective section has explored how systems thinking intersects with broader questions of capitalism, sustainability, and cultural transformation. By examining alternative economic models, the power of literature and storytelling, and the implications for governance, we see that systems thinking is not merely a technical tool, but a transformative lens for reimagining society (Martinez-Alier 2021).

To move forward, we must embrace systems thinking not just in science and policy, but in education, culture, and everyday practice, building a world that honours complexity, nurtures interdependence, and sustains life for generations to come.

Conclusions

This article has demonstrated how systems thinking and emergy analysis provide powerful frameworks for understanding and managing estuaries, complex, dynamic ecosystems at the interface of freshwater and marine environments. By adopting a systems' perspective, we move beyond fragmented interventions to address root causes, feedback mechanisms, and long-term sustainability.

Estuaries are not isolated entities but are embedded within larger ecological, economic, and social systems. Traditional reductionist approaches often fail to capture the full complexity of these environments, leading to ineffective or even counterproductive management strategies. These fragmented methods tend to isolate individual components, such as water quality or fish populations, without considering how they interact with broader processes like nutrient cycling, land-use change, or socio-economic pressures. As a result, interventions may address symptoms rather than root causes, exacerbating problems in the long term.

Systems thinking offers a more integrated alternative, emphasizing feedback loops, emergent properties, and multiscale interactions that shape estuarine health. By adopting this perspective, managers can design interventions that align with natural processes and support both ecological integrity and human well-being. This shift from fragmentation to integration is essential for ensuring the sustainability of estuaries in the face of growing environmental and societal challenges.

Key findings on this work include: (1) Estuaries exhibit emergent properties such as biodiversity, carbon sequestration, and water filtration that arise from interactions among physical, chemical, and biological components. (2) Feedback loops play a central role in shaping estuarine dynamics. Positive feedback can amplify disturbances (e.g., eutrophication), while negative feedback helps maintain stability (e.g., wetland nutrient absorption). (3) Emergy analysis,

by quantifying all inputs in solar emjoules, offers a unified metric to evaluate ecosystem services, human impacts, and sustainability trade-offs. (4) Case studies, including the Herring River Estuary restoration, mangrove rehabilitation in Southeast Asia, and Liaohe Estuary wetland conservation, illustrate how systems principles inform effective, adaptive management. (5) Systems theory reveals how changes in upstream land use, climate patterns, and anthropogenic pressures propagate through estuarine systems, highlighting the need for integrated, cross-sectoral planning.

These insights underscore the importance of viewing estuaries not as isolated environments, but as integrated components of broader systems where interactions, storages, and transformations shape resilience and functionality. They highlight how estuaries are influenced by upstream river flows, coastal dynamics, and human activities, all of which interact in complex ways to determine ecological health. Recognizing these interconnections allows for more effective management that addresses root causes rather than symptoms. It also emphasizes the need to protect not just the estuary itself, but the entire watershed and coastal zone that influence it. By adopting this systems' perspective, conservation, and restoration, efforts can better support long-term sustainability and adaptability in the face of environmental change.

Systems thinking contributes to estuary management by emphasizing holism, interdependence, and feedback mechanisms, enabling researchers and policymakers to design interventions that align with natural processes rather than disrupt them. The integration of emergy analysis adds a quantitative dimension to this approach, offering several key benefits. (a) It allows for the comparison of diverse flows (natural and human-driven) using a common unit, solar emjoules, making it possible to assess the relative value and sustainability of different system components. (b) It distinguishes between renewable and non-renewable inputs, revealing whether an estuary relies primarily on sustainable energy sources or unsustainable human interventions. (c) It supports policy development and decision-making by identifying leverage points for intervention, such as restoring wetlands, reducing pollution, or promoting sustainable aquaculture.

Together, systems thinking and emergy analysis enable a regenerative approach to estuary management, one that balances ecological integrity, economic viability, and social equity. Based on the insights developed throughout this article, the following policy recommendations are proposed:

a. Integrate systems thinking into coastal and estuarine planning

Policymakers should adopt adaptive, interdisciplinary frameworks that recognize estuaries as part of larger watershed and coastal systems. This includes incorporating systems indicators (e.g., transformity, yield ratio, environmental loading ratio) into environmental assessments and monitoring programs.

b. Promote emergy-based decision-making

Governments and institutions should support the use of emergy synthesis in evaluating the sustainability of estuarine ecosystems. This would help quantify the true value of ecosystem services, guide resource allocation, and identify areas most vulnerable to degradation.

c. Support nature-based solutions and restoration efforts

Investing in wetland restoration, mangrove protection, and living shorelines enhances estuarine resilience to climate change, sea level rise, and pollution. These nature-based solutions also offer co-benefits such as carbon sequestration, habitat creation, and community livelihood support.

d. Strengthen stakeholder engagement and co-management

Effective estuary governance requires collaboration among scientists, local communities, fishers, farmers, and policymakers. Participatory models ensure that decisions reflect both ecological realities and social needs, fostering ownership and long-term success.

e. Shift from growth-oriented policies to regenerative models

Given the limits of capitalist growth logic, policies must prioritize well-being, regeneration, and ecological balance over GDP expansion. This includes supporting decentralized economies, circular systems, and community-led conservation initiatives.

To further advance the application of systems thinking and emergy analysis to estuaries, future research should focus on different areas such as long-term monitoring using emergy indicators, establishing longitudinal datasets that track emergy flows over time will enhance our ability to detect trends, evaluate restoration outcomes, and adapt management strategies accordingly. Another area could be comparative studies across diverse estuarine systems, expanding emergy-based research to different types of estuaries, tropical vs. temperate, urbanized vs. pristine, will improve our understanding of variability and resilience across contexts.

Integration of indigenous and local ecological knowledge should also be a focus of attention. Incorporating indigenous knowledge systems into scientific models can enrich our understanding of estuarine dynamics and promote culturally grounded conservation strategies that have stood the test of time. Digital Tools and Modelling Platforms are also important as developing open-access tools and visualization platforms for emergy modelling will make systems analysis more accessible to students, practitioners, and policymakers, accelerating its adoption in education and planning.

Scaling up to global estuarine networks as a future work, should explore how individual estuarine systems contribute to global biogeochemical cycles, particularly in terms of carbon storage, nutrient cycling, and biodiversity corridors. This will support international cooperation on coastal conservation and climate mitigation.

As final thoughts, estuaries serve as powerful microcosms for addressing broader planetary challenges, from climate change and biodiversity loss to social inequality and unsustainable development. Their study through systems and emergy lenses offers valuable insights applicable to other ecosystems and socio-environmental contexts.

Ultimately, this article underscores that true sustainability requires a paradigm shift, from viewing nature as a resource to be exploited, to seeing it as a partner in co-producing resilience and well-being. By embracing systems thinking, critical

reflection, and cultural re-engagement, societies can move toward a future that is not only sustainable, but also just, regenerative, and deeply connected.

Additional information

Conflict of interest

The author has declared that no competing interests exist.

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No ethical statement was reported.

Use of AI

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Data availability

All of the data that support the findings of this study are available in the main text.

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